COLD-ELECTRON BOLOMETER WITH STRONG ELECTROTHERMAL FEEDBACK

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ABSTRACT

A novel concept of the Cold-Electron Bolometer (CEB) based on strong ***direct electron cooling*** of the absorber has been proposed. This concept is purposed to overcome the unavoidable contradiction of supersensitive detectors between supersensitivity and supersaturation due to background power load. The effective electron cooling can be treated as strong electrothermal feedback (ETF) similar to TES (transition-edge sensor) in voltage-biased mode. However, in contrast to TES, an additional artificial dc heating for electrothermal feedback is replaced by deep electron cooling removing all incoming power from the absorber to the next stage and keeping minimum temperature (less than phonon temperature for small level of power). The CEB can be treated as "0-detector" in comparison with TES treated as "Tc-detector". Noise properties (NEP) are considerably improved by decreasing the electron temperature. It could mean principle breakthrough in realization of supersensitive detectors. All incoming power is removed from supersensitive absorber to the next stage of readout system – a SQUID with considerably higher dynamic range. As in TES, the strong ETF (up to 1000) decreases the response time of CEB from e-ph time (≅10 μs) to cooling (tunneling) time (≅10 ns)

The estimations show that it is realistic to achieve NEP of the order of 10^{--19} W/Hz$^{1/2}$ with SQUID readout system at 100 mK and 10^{--18} W/Hz$^{1/2}$ at 300 mK. At 2 K the theoretical evaluations show that the expected NEP is of the order of $2x10^{-16}$ W/Hz$^{1/2}$ and increases to the level of $8x10^{-16}$ W/Hz$^{1/2}$ for background load of 100 pW.

INTRODUCTION

In the last decade superconducting detectors have become the most sensitive radiation detectors of Sub-mm, Infrared, and Optical radiation with an estimated ultimate sensitivity down to 10^{-20} W/Hz$^{1/2}$ [1]. A few modest imaging arrays for ground-based sub-mm observations are already operational and plans for building significant larger arrays are approved. Ultra-low-noise bolometers are required for space-based astronomical observations. The two proposed NASA missions, SPIRIT and SPECS, determine the highest level of requirements for bolometers for nearest future. The detector goal is to provide noise equivalent power less than 10^{-20} W/Hz$^{1/2}$ [2] over the 40 – 500 μm wavelength range in a 100x100 pixel detector array. No one existing technology could satisfy these requirements. The proposed CEB concept could be a good candidate to become a leading concept in this development.

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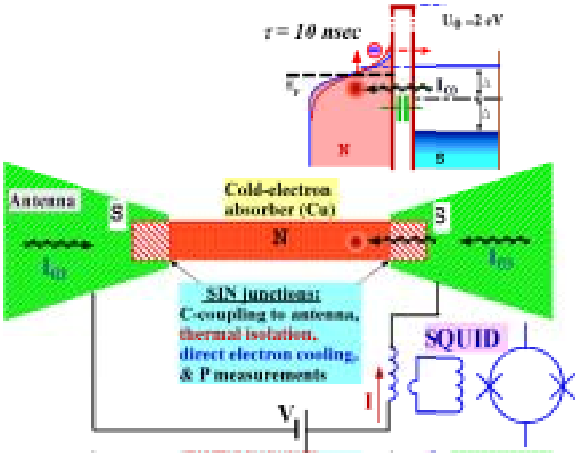

*Fig. 1. Capacitively coupled Cold-Electron Bolometer (CEB) with SIN tunnel junctions for **direct electron cooling** and **power measurement** . The highest sensitivity (due to low Te) is combined with fastest time response (around 10 ns) determined mainly by tunneling time*

For the moment, the most developed superconducting bolometer is TES (transition-edge sensor) with strong electrothermal feedback [3]. However, the TES has some problems with excess noise, saturation, and the most drastic problem of artificial overheating by dc power for the feedback. This additional heating kills all efforts on deep cooling and does not give good perspectives for realization of limit performance of the bolometer.
In contrast to this overheating, the principle new concept of a "***Cold-Electron" Bolometer (CEB)*** with direct electron cooling (Fig. 1) has been proposed by Kuzmin et al. [4,5]. The CEB is the only concept suggesting effective removing incoming background power from supersensitive region of absorber. This concept has good perspectives because it returns system to lowest temperature (noise) state with highest responsivity to the signal. All signal power is used for measurements (without lost to e-ph leackage). Time constant is determined by tunneling time that is at 2-3 orders of magnitude shorter than e-ph time and could be estimated as 10 ns [6]. This bolometer can be especially effective for operation in the presence of a real background power load. The optimal realization of this sensor proved to be a two junction ***cold-electron bolometer with capacitive coupling*** to the antenna [7].Theoretical estimations and preliminary experiments show that it is possible to realize the necessary sensitivity of better than 10^{-18} W/Hz$^{1/2}$ with antenna-coupled nanobolometers at a temperature ≤0.3 K. Additional advantages of such detectors are easy integration in arrays and the possibility of polarization measurements.

Comparison of CEB and TES

The operation of CEB can be analyzed using a heat balance equation [8]:

$$P_C(V,T_e,T_{ph})+\Sigma\Lambda(T_e^5-T_{ph}^5)+C_\Lambda\frac{dT}{dt}=P_0+\delta P(t) \qquad (1)$$

Here, $\Sigma\Lambda(T_e^5-T_{ph}^5)$ is the heat flow from electron to the phonon subsystems in the normal metal, Σ is a material constant, Λ - a volume of the absorber, T_e and T_{ph} are, respectively, the electron and phonon temperatures of the absorber; $P_{cool}(V,T_e,T_{ph})$ is cooling power of the SIN tunnel junctions; $C_\Lambda = \gamma T_e$ is the specific heat capacity of the normal metal; and *P(t)* is the incoming rf power. We can separate Eq. (1) into the time independent term, $\Sigma\Lambda(T_{e0}^5-T_{ph}^5)+P_{cool0}(V,T_{e0},T_{ph})=P_0$, and the time dependent term, $(\frac{\partial P_{cool}}{\partial T}+5\Sigma\Lambda T_e^4+i\omega C_\Lambda)\delta T=\delta P$. The first term, $G_{cool}=\delta P_{cool}/\partial T$, is the cooling thermal conductance of the SIN junction that gives the negative electrothermal feedback (Fig. 2a), the second, $G_{e-ph}=5\Sigma\Lambda T_e^4$, is electron-phonon thermal conductance of the absorber.

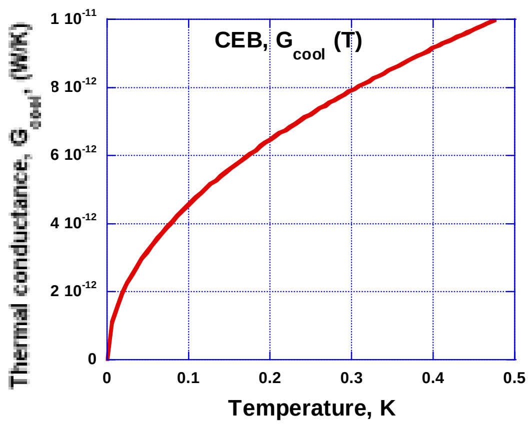

*Fig. 2b: Cooling conductance of CEB for operation near "**T=0**" (possible minimum T).*

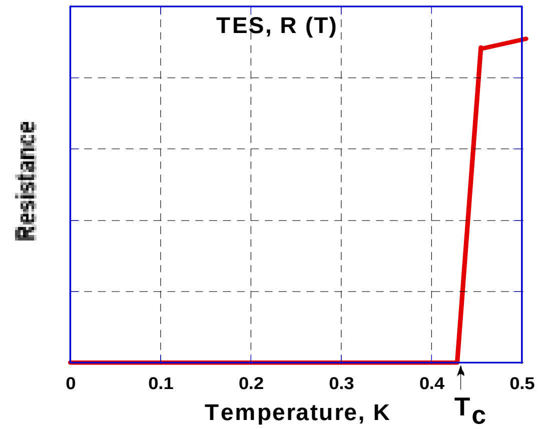

Fig. 2b:** Nonlinear resistance of TES for operation near **Tc

The current resposivity is given by

$$S_i = \frac{\partial I}{\partial P} = \frac{\partial I/\partial T}{G_{cool} + G_{e-ph} + i\omega C_\Lambda} = \frac{\partial I/\partial T}{G_{cool}} \frac{L}{(L+1)[1+i\omega\tau]}, \qquad (2)$$

where $L = G_{cool}/G_{e-ph} >> 1$ is ETF gain, and $\tau = \tau_0/(L+1)$ is an effective time constant, $\tau_0 = C_\Lambda/G_{e-ph}$ ($\cong 10\ \mu s$ at 100 mK). It is clear that the effective thermal conductance is increased by the effect of cooling (negative ETF) and time constant is proportionally decreased. These formulae for S_i are similar to TES ones with replacement of $(\partial I/\partial T)/G_{cool}\ (\cong e/kT)$ by $1/V_b$. We compare now the basic paramters of CEB and TES (Fig 2-4).

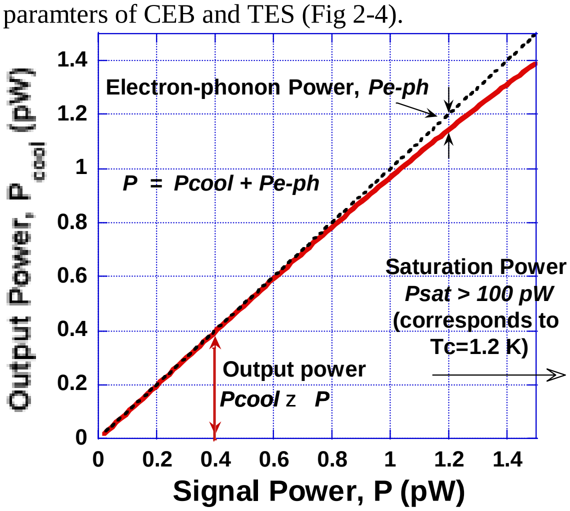

Fig. 3a: Output (cooling) power of CEB in dependence on Signal power (they are almost equal). There is no Saturation power at these level of signal and saturation can be achieved only after heating to Tc of Al electrode (P_{sat} around 100≅pW) .

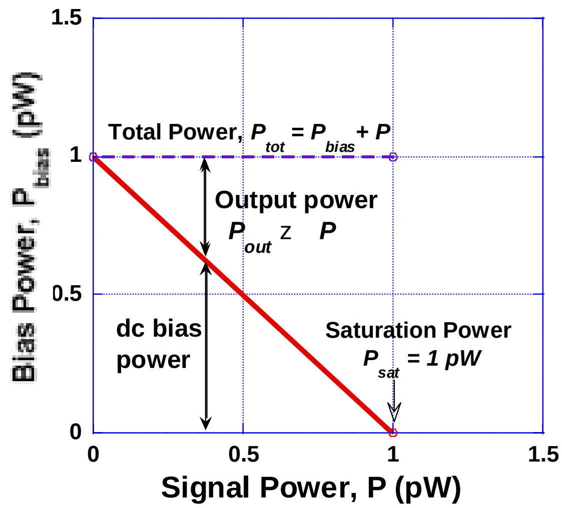

***Fig. 3b:** Bias power and Output power of TES in dependence on Signal power. Saturation power is equal to bias power without signal. To increase P_{sat}, the P_{bias} should be increased (but it leads to increase of T and NEP).*

Due to strong ETF the output power is equal to signal power in both cases. The only difference is that for TES the Pout is decrease of dc bias power meanwhile for CEB the Pout is the directly removed power Pcool by cooling junctions.

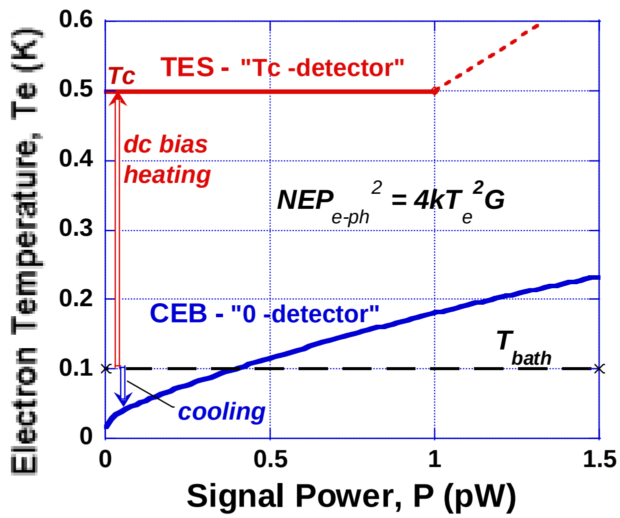

Fig. 4: *Electron temperature as a function of signal power for T_{bath}=100 mK. For P<0.4pW, the T_e of CEB is less than T_{bath} (real Cold-Electron Bolometer mode)*

The Fig. 4 shows principle difference of TES and CEB: TES is working near Tc and supports this temperature decreasing dc heating by ETF proportionally to the received signal. On the contrary, CEB is working near zero temperature (possible available minimum of Te) and removes incoming power from the absorber by tunnel junctions. As the result, all properties of CEB are determined by low temperature (NEPe-ph is shown in Fig. 4) meanwhile for TES it is always Tc even for very small signals.

Noise properties of CEB are characterized by the noise equivalent power (*NEP*):

$$NEP^2_{total} = NEP^2_{e-ph} + NEP^2_{SIN} + \frac{\delta I^2}{S_I^2}. \qquad (3)$$

Here $NEP^2_{e-ph} = 10 k_B \Sigma\Lambda (T_e^6 + T_{ph}^6)$ is the noise associated with electron-phonon interaction; NEP^2_{NIS} is the noise of the NIS tunnel junctions, and the last term, $\delta I^2/S^2_I$, is the noise of the amplifier (SQUID). The noise of the NIS tunnel junctions, NEP^2_{NIS}, has three components: shot noise $2eI/S^2_I$, the fluctuations of the heat flow through the tunnel junctions and the correlation between these two processes $NEP^2_{SIN} = \delta P^2_\omega - 2\frac{\delta P_\omega \delta I_\omega}{S_I} + \frac{\delta I^2_\omega}{S_I^2}$. Due to this correlation the short noise is decreased at 30-50%. Similar correlation is in TES decreasing Johnson noise. The estimations for CEB show that it is realistic to achieve NEP of the order of 10^{-19} W/Hz$^{1/2}$ at 100 mK and 10^{-18} W/Hz$^{1/2}$ at 300 mK [7].

CEB at 2 K

The operation of CEB has been analyzed at 2K for typical parameters of the bolometer: T_c =9 K (Nb), Λ= 0.002 μm^3, R= 1 kΩ, S_{SQUID} =10 fA/Hz$^{1/2}$ (Fig. 5a). The change of NEP components in the presence of background power load 100 pW is shown in Fig. 5a. Electron-phonon conductance $G_{e-ph} = 5\Sigma\Lambda T_e^4$ is replaced at this temperature by Kapitza resistance $R_K = K / T_{ph}^3$, where A is an area of the interface and K is material constant: for copper-plastic interface K=7.5x10^{-4} K^{4}m^2/W [9]. Second term in Eq. 1 is replaced by $K\Lambda(T_e^4 - T_{ph}^4)$.

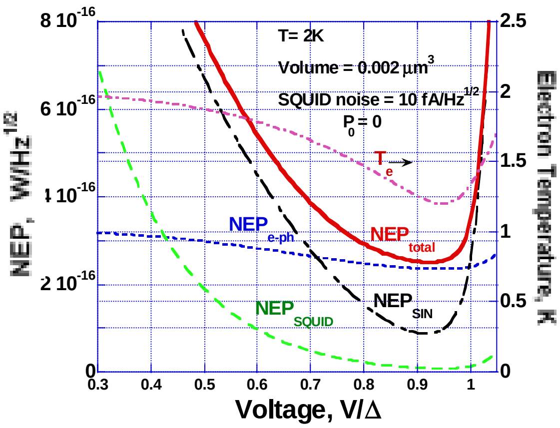

Fig. 5a. NEP components and electron temperature of the CEB in dependence on voltage for Λ= 0.002 μm^3, R = 1 kΩ, S_{SQUID} = 10 fA/Hz$^{1/2}$, and bath temperature 2 K;

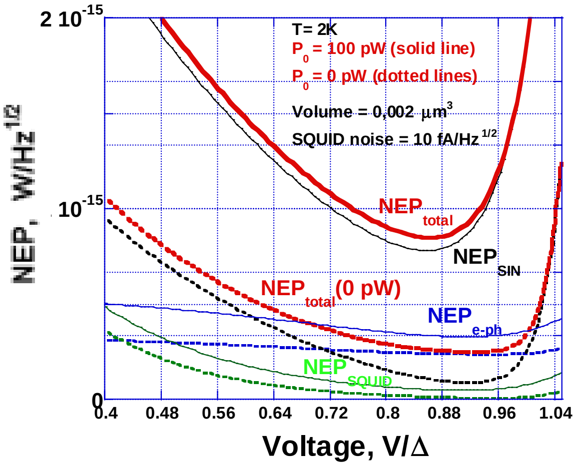

Fig. 5b. NEP of the CEB in presence of the background load 100 pW (solid line) and without it (dashed line) for the same bolometer parameters.

The theoretical evaluations show that the expected NEP is of the order of $2x10^{-16}$ W/Hz$^{1/2}$ without load and increases to level of $8x10^{-16}$ W/Hz$^{1/2}$ for background load of 100 pW. Cooling ability of CEB make it possible to keep relatively low NEP at T=2 K with moderate decrease of Te to 1.2 K.

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